Deep Galaxy Surveys in the 9150 Å Airglow Window

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Abstract. We describe the current status of two complementary programs to search for objects with strong emission lines in a ~ 300 Å gap, centered at 9150 Å, in the strong airglow emission. Both programs are being carried out with LRIS on the Keck II telescope. The first of these uses broad-band and narrow-band filter photometry to select candidates, followed by multi-slit spectroscopy through the same narrow-band filter to limit the bandpass and allow a dense packing of slits. The second uses six parallel long slits to carry out a blind spectroscopic search through the filter isolating the 9150 Å window. The total slit area covered ranges from 1 to 3.5 square arcmin per pointing, depending on slit width, and we can obtain 3σ detections of emission lines of $< 2 \times 10^{-18}$ erg cm^{-2} s^{-1} in a 12000 s observation with $1''.5$ slits.

Because, for faint objects in both programs, we are most sensitive to strong lines with large equivalent widths, most of our detections will be restricted to a few specific emission lines at certain discrete redshifts. One of the more interesting possibilities is Ly-α at $z \sim 6.5$. However, even with 12000 s integrations on the Keck II telescope, our narrow-band imaging does not pick up objects with emission-line fluxes $\lesssim 10^{-17}$ erg cm^{-2} s^{-1}. With this limit, at $z \sim 6.5$, we would pick up only the most luminous of the $z > 5$ objects discovered so far. Our blind spectroscopic search potentially has a better chance of discovering such objects, but we have not yet found any definite examples in the limited area of the sky we have covered to date. We discuss the criteria for identifying Ly-α emission in noisy spectra and emphasize how high-ionization dwarf galaxies at low redshift can be mistaken for Ly-α candidates under certain conditions.

Keywords: galaxies, airglow, spectroscopy

1. Introduction

Our knowledge of the distant universe has grown immensely over the past few years, thanks largely to methods that have been developed to isolate populations of high-redshift galaxies from other faint objects. Many of these methods depend on measuring Ly-α emission or the continuum discontinuity caused by the Ly-α forest and the Lyman break. These techniques can be effective with large ground-based telescopes up to $z \sim 5$; at higher redshifts the observations are seriously compromised by the strong OH airglow emission from the upper atmosphere.

As Fig. 1 shows, although the OH airglow bands become a major problem longward of 7240 Å, there are still small portions of the spectrum that are relatively uncontaminated, principally the bandpasses 200–300 Å wide centered around 8150 Å and 9150 Å. In these regions,

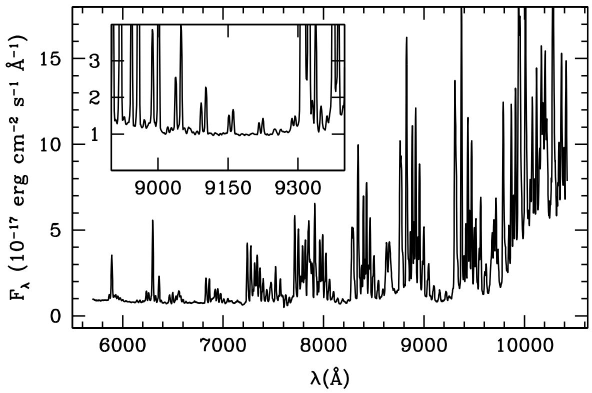

Figure 1. The airglow spectrum under dark conditions from Mauna Kea, obtained with LRIS on Keck I. The inset shows an enlargement of the region around 915 nm.

the average sky brightness is hardly worse than it is in the R band. We have chosen to concentrate on the 9150 Å band, since it is the longest-wavelength clear region accessible to CCD detectors.

A combination of advances in detector development, advances in large interference filter design and manufacture, and the availability of 8–10 m class telescopes now makes it possible to exploit this window for a range of issues in extragalactic astronomy that have previously been out of reach. Some of these form a natural bridge to topics that will be central to the expected program for the New Generation Space Telescope.

2. Scientific Rationale

The essential feature of our program is the detection of faint objects having fairly strong emission lines with large equivalent widths. Most of our detections will be one of the following: Hα at $z \sim 0.39$; [O III] $\lambda\lambda$4959,5007 at $z \sim 0.83$; [O II] λ3727 at $z \sim 1.45$; or (possibly) Ly-α at $z \sim 6.5$. Perhaps surprisingly, we can usually decide among these possibilities from spectra covering only a ~ 300 Å region.

Because we are investing a lot of telescope and analysis time in each of the fields we investigate, we have attempted to combine the emission-line search with other programs that require deep imaging and/or spectroscopy. In particular, we have targeted either (1) 3C radio source fields that would place the [O II] λ3727 doublet within the 9150 Å window, or (2) quasar fields with $1.4 < z < 1.7$ in which we have old galaxy candidates requiring deep spectroscopy for confirmation.

There are obviously many interesting programs that can come out of the very deep flux-limited samples we will eventually have for large numbers of Hα and [O III] emission-line sources, as well as smaller numbers of [O II] sources, but we do not have space to discuss them here. Instead, we will concentrate on the possibilities for detection of Ly-α emitting galaxies at $z \sim 6.5$.

Early searches for so-called "primeval galaxies" were more-or-less predicated on a picture of bulge and E galaxy formation in which essentially all of the star formation takes place within a collapse time scale (Eggen *et al.*, 1962). Predicted luminosities and Ly-α fluxes were accordingly very high, and the lack of detections of such objects in the early surveys (Pritchet and Hartwick, 1987, 1990; see also de Propris *et al.*, 1993; Thompson and Djorgovski, 1995) was disillusioning, although it did spur efforts to rethink galaxy formation mechanisms. Views on galaxy formation have shifted radically over the past decade, partly as a result of the recognition of the controlling role played by dark matter and of the growing power and sophistication of n-body simulations of the early Universe, combined with semi-analytic treatments of dissipation and star formation (*e.g.,* Kauffmann *et al.*, 1999; Cole *et al.*, 1998; Governato *et al.*, 1998). According to the current view, most galaxy formation takes place via the accumulation of baryonic matter within dark matter haloes, and the gradual merger of these baryonic "seeds" as the dark matter haloes merge. The timing of star formation (and thus the formation of "galaxies" in the usual sense) depends on the relative time scales for mergers (with resultant shock heating of the gas) and for cooling processes (which will be inefficient for primordial material).

In the optical/IR regime, observational approaches towards discovering high-redshift galaxies have tended to emphasize photometric redshift determinations based largely on absorption by the Ly-α forest and the Lyman limit (Steidel *et al.*, 1995,1996; Madau *et al.*, 1996; Lanzetta *et al.*, 1996; Fernádez-Soto *et al.*, 1998). Thompson *et al.* (1994) discuss the possibility of using narrow-band imaging in the IR. However, as Hu *et al.* (1998) have emphasized, there is still a place for Ly-α emission searches, since there should be very little dust present in the very first galaxy generation. In fact, such searches should be biassed in favor of objects approaching truly "primeval" galaxies. Determining the nature of such objects is a crucially important component for our understanding of the early phases of galaxy formation in the Universe.

Within the past year or so, a number of objects with $z > 5$ have been claimed, most based at least partly on Ly-α emission (Dey *et al.*, 1998; Hu *et al.*, 1998, 1999; Weymann *et al.*, 1998; Spinrad *et al.*, 1998; Chen *et al.*, 1999). Some of these, at least, are quite solid and convincing. Our

purpose is to investigate the possibility of the developing of significant samples of objects at $z \sim 6.5$. Ly-α selection of objects at this redshift will give us a unique window on the nature of early galaxy formation in the Universe. One can use the observed Ly-α fluxes, somewhat cautiously, to make estimates of star-formation rates, and therefore the contribution of such objects to the UV ionizing continuum. The two concerns are the effect of the Ly-α forest in removing flux from the emission profile, and the effect of even very small amounts of dust on this resonance line. However, (Hu *et al.*, 1998) find that the equivalent widths in their filter-selected samples (redshifts 3.4 and 4.5) were close to the maximum expected for ionization by stars, leaving little room for dust extinction. In any case, one can at least determine a lower limit to the star-formation rate.

3. Observational Strategies

Our filter photometric selection uses three filters: a narrow-band filter with a center wavelength of 9148 Å and a FWHM of 274 Å (henceforth N_{915}), an RG-850 filter combined with the CCD response cutoff (henceforth Z), and an R-band filter. The N_{915} and Z filters have almost the same effective central wavelengths, but the bandpass of the latter is abouth 5 times larger, so emission-line objects can be recognized from photometry using these two filters alone. The R image is useful to look for objects that are also R-band dropouts. We carry out automated photometry of the N_{915} image to produce a catalog of objects detected above a given threshold. We then do the photometry at corresponding positions of the Z and R images. Objects that are not detected in the Z filter are generally considered spurious (although this criterion means rejecting some sources with weak, large-equivalent-width lines). From this photometry, we can construct samples of emission-line candidates, with or without R-band dropout criteria.

For spectrographic confirmation, we first obtain multislit spectra of candidates through the N_{915} filter, and with moderately high dispersion. This procedure allows us to obtain simultaneous spectroscopy of > 100 objects at once, but only with very restricted wavelength coverage. Nevertheless, we can often obtain a firm redshift from these spectra alone: Hα often is accompanied by [N II] λ6583; in about 2/3 of the cases where we see [O III] λ5007, [O III] λ4959 is also within the bandpass; we can resolve [O II] λ3727; and we should also be able to resolve the expected profile asymmetry in Ly-α caused by absorption of the blueward wing by the Ly-α forest. For cases that remain uncertain,

we obtain conventional wide-band multislit spectroscopy in order to pick up other spectral features.

In order to go to fainter limits than is possible with filter photometry, we have also attempted a blind spectroscopic search. We still limit our bandpass with the N_{915} filter, allowing us to use 6 parallel long slits simultaneously. The targets of interest are mostly $\lesssim 1''$ in size, so we can adjust the slit widths to trade between sky coverage and sensitivity without seriously compromising spectral resolution. We have used both $1\farcs5$ and $5''$ slits in our observations to date. For wide-bandwidth followup spectroscopy of candidates, we use conventional multislit masks, with the slitlets oriented nearly perpendicular to the long slits (since, especially for the wider parallel slits, the position of an object within the width of the slit is uncertain).

4. Results

4.1. Observing Program

We have carried out some pilot programs with Keck II/LRIS in the fields of 3C 298 and 3C 437 using imaging selection and in the fields of 3C 280.1 and 4C 15.55 using spectroscopic selection. The total integrations in our three filters for the 3C 298 and 3C 437 fields were, respectively, 6000 s and 22800 s in N_{915}, 6000 s and 10800 s in Z, and 2700 and 12000 in R. While the total integrations were in all cases longer for the 3C 437 field, observing conditions were more variable, so the longer integrations did not give the detectivity gain that one might have expected. Our 3σ AB magnitude formal limits in a $2''$-diameter aperture were 25.4, 26.2, and 27.2 for the 3C 298 field for the N_{915}, Z, and R filters, respectively, and 25.7, 26.2, and 28.0 for the 3C 437 field for the same filters. These correspond to detection limits for emission lines in the N_{915} filter of $\sim 3 \times 10^{-17}$ erg cm^{-2} s^{-1} for the 3C 298 field and $\sim 2 \times 10^{-17}$ erg cm^{-2} s^{-1} for the 3C 437 field. Because our images are typically $0\farcs7$ FWHM or better, we can actually use smaller apertures and improve on these formal limits by about a factor of 2. For our spectroscopic selection images from $1\farcs5$ slits, with a typical integration of ~ 12000 s, the emission-line limit (again, 3σ) was $\sim 1.5 \times 10^{-18}$ for an aperture with a diameter of $2''$ in the spatial direction and 12 Å in the dispersion direction, and in a region free of airglow lines. For nearly stellar objects, the limit was about twice this when we used $5''$ slits. As a reference, the emission-line flux of the galaxy SSA22-HCM1, at $z = 5.74$ (Hu *et al.*, 1999), would correspond to 1.1×10^{-17} (1.3×10^{-17}) erg cm^{-2} s^{-1} if it were seen at $z = 6.5$, assuming $q_0 = 0$ (0.5).

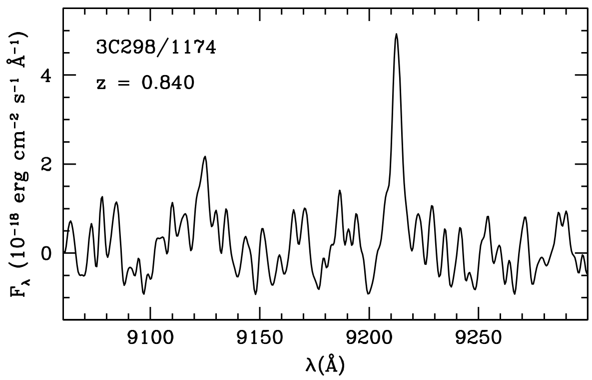

Figure 2. An example of a faint emission object in our 3C 298 field. The object has magnitude $AB_{9150} = 26.8$ in the RG850 filter. The two lines visible in this spectral region are [O III] $\lambda\lambda$4959,5007, at a redshift of 0.84. The [O III] λ5007 line has a flux of 3×10^{-17} erg cm^{-2} s^{-1}.

We have only just begun exploring these datasets, and we have not yet found any firm Ly-α detections, although we have a number of possible candidates. Our observations cover ~ 40 square arcmin in imaging mode and ~ 5 square arcmin in spectroscopic mode. Unfortunately, at this stage we cannot place useful limits on star-formation rates in Ly-α emitters at $z \sim 6.5$ because of the incompleteness of our spectroscopic follow-up. Figure 2 shows an example of a spectrum of a faint object found in our 3C 298 field.

4.2. Line Identification Pitfalls

Because luminous Ly-α emitters at very high redshift are quite rare, an argument in favor of identifying a given line as Ly-α solely by a process of elimination must always be viewed with some suspicion. Figure 3 shows the spectrum of a faint object from our spectroscopy of the 3C 212 field (Stockton and Ridgway, 1998). The strong emission line at 8567 Å has an observed equivalent width of 640 Å, and no other emission lines are apparent over the observed wavelength range from 6855 to 9477 Å. One can eliminate most of the obvious possibilities, and at one point we thought that the line might be Ly-α. But careful measurement of the extremely weak continuum showed no discontinuity across the line, and we finally determined that the line must be Hα, in spite of the absence of [N II] λ6583, by finding very weak He I λ5876 emission. Similar objects, though rare, are known locally; an example is shown in Fig. 4o of Terlevich *et al.* (1991). The low metallicities and high ionizations of such objects combine to almost totally suppress low-ionization metal lines. Note that if our spectral range had extended to

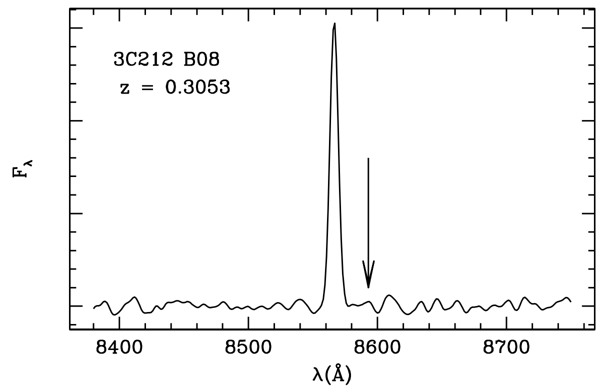

Figure 3. The spectrum of the region near the Hα line in a magnitude 25 ($AB_{700\mathrm{nm}}$) object in the field of 3C 212. The arrow shows the expected position of [N II] λ6583. The identification of the line as Hα was based on the detection of weak He I λ5876 emission. See Stockton and Ridgway (1998) for more details.

slightly bluer wavelengths, we would have detected very strong [O III] emission, which would have resolved the issue immediately.

We do have a fair number of cases showing only a single, moderately strong emission line in our 300 Å bandpass. For most of these, we can eliminate the possibility that they are either [O II] λ3727 or [O III] $\lambda\lambda$4959,5007. The observed equivalent widths are typically > 200 Å, and, if the emission is connected with star formation, almost the only plausible possibilities are Hα in a low-metallicity dwarf galaxy, Hβ in almost any active starburst galaxy, or Ly-α; the higher Balmer lines and most other lines are unlikely to have such large equivalent widths. A fairly strong test would be to obtain good spectroscopy covering the region near 7000 Å, where [O II] λ3727 would fall if the line in the 9150 Å window is Hβ, and where [O III] λ5007 would fall if the line is Hα.

4.3. Future Plans

In trying to carry out complete campaigns on our fields in a single observing season, we have targeted only the most obvious emission-line candidates. We plan now to do a more thorough look at each of our fields. Our imaging data so far goes to a depth that is likely right on the edge of detecting the brightest Ly-α sources at $z \sim 6.5$. We hope to be able to double our present effective imaging integration time in these two fields. Over the slightly longer term, we plan to bring this program to the Subaru telescope prime focus camera, where the field of $24' \times 30'$ and the use of deep-depletion CCDs (which will double our quantum efficiency at 9150 Å) will give us a factor of 40 improvement in throughput.

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